15-819M: Data, Code, Decisions

06b: Java Modeling Language

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Outline

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JML Expressions ≠ JAVA Expressions

boolean JML Expressions (to be completed)

- each side-effect free `boolean` JAVA expression is a `boolean` JML expression
- if `a` and `b` are `boolean` JML expressions, and `x` is a variable of type `t`, then the following are also `boolean` JML expressions:
  - `!a` ("not a")
  - `a && b` ("a and b")
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  - `a ==> b` ("a implies b")
  - `a <==> b` ("a is equivalent to b")
  - ...
  - ...
  - ...
  - ...

Beyond `boolean` JAVA expressions

How to express the following?

- an array `arr` only holds values ≤ 2

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First-order Logic in JML Expressions

JML `boolean` expressions extend JAVA `boolean` expressions by:

- implication
- equivalence

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JML `boolean` expressions extend JAVA `boolean` expressions by:

- implication
- equivalence
- quantification

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  - `(\forall t x; a)` (“for all `x` of type `t`, a is true”)
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  - `(\exists t x; a)` ("there exists x of type t such that a")
  - `(\forall t x; a; b)` ("for all x of type t fulfilling a, b is true")
  - `(\exists t x; a; b)` ("there exists an x of type t fulfilling a, such that b")

JML Quantifiers

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Range predicate forms are redundant:

`(\forall t x; a; b)`
equivalent to
`(\forall t x; a ==> b)`

`(\exists t x; a; b)`
equivalent to
`(\exists t x; a && b)`

Pragmatics of Range Predicates

`(\forall t x; a; b)` and `(\exists t x; a; b)`

widely used

pragmatics of range predicate:

`a` used to restrict range of `x` further than `t`

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(\forall int i,j;
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```
(\forall int i,j; 0<=i && i<j && j<10;
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example: "`arr` is sorted at indexes between 0 and 9":

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(\forall int i,j; 0<=i && i<j && j<10; arr[i] <= arr[j])
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(\forall int i; 0<=i && i<arr.length; m >= arr[i])
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is this enough?

Using Quantified JML expressions

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(\exists int i; 0<=i && i<arr.length; m == arr[i])
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Using Quantified JML expressions

How to express:

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arr.length>0 ==>
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Careful!

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```
(\forall int i; 0<=i && i<maxAccountNumber;
                accountProxies[i].accountNumber == i )
```

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```
(\forall BankCard p1, p2;
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- JML quantifiers range also over non-created objects

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Domain of quantification

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- same for quantifiers in KeY!
- in JML, restrict to created objects with `\created`
- in KeY? ($\Rightarrow$ upcoming lecture)

Outline

Example: Specifying LimitedIntegerSet

```
public class LimitedIntegerSet {
  public final int limit;
  private int arr[];
  private int size = 0;

  public LimitedIntegerSet(int limit) {
    this.limit = limit;
    this.arr = new int[limit];
  }
  public boolean add(int elem) {/*...*/}

  public void remove(int elem) {/*...*/}

  public boolean contains(int elem) {/*...*/}

  // other methods
}
```

Prerequisites: Adding Specification Modifiers

```
public class LimitedIntegerSet {
  public final int limit;
  private /*@ spec_public @*/ int arr[];
  private /*@ spec_public @*/ int size = 0;

  public LimitedIntegerSet(int limit) {
    this.limit = limit;
    this.arr = new int[limit];
  }
  public boolean add(int elem) {/*...*/}

  public void remove(int elem) {/*...*/}

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Specifying contains()

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How to specify result value?

Result Values in Postcondition

In postconditions,
one can use '**\result**' to refer to the return value of the method.

```
/*@ public normal_behavior
  @ ensures \result ==
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/*@ public normal_behavior
  @ ensures \result == (\exists int i;
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  @
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one can use '**\result**' to refer to the return value of the method.

```
/*@ public normal_behavior
  @ ensures \result == (\exists int i;
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  @                              arr[i] == elem);
  @*/
public /*@ pure @*/ boolean contains(int elem) {/*...*/}
```

Specifying add() (spec-case1)

```
/*@ public normal_behavior
  @ requires size < limit && !contains(elem);
  @ ensures \result == true;
  @ ensures contains(elem);
  @ ensures (\forall int e;
  @                   e != elem;
  @                   contains(e) <==> \old(contains(e)));
  @ ensures size == \old(size) + 1;
  @
  @ also
  @
  @ <spec-case2>
  @*/
public boolean add(int elem) {/*...*/}
```

Specifying add() (spec-case2)

```
/*@ public normal_behavior
  @
  @ <spec-case1>
  @
  @ also
  @
  @ public normal_behavior
  @ requires (size == limit) || contains(elem);
  @ ensures \result == false;
  @ ensures (\forall int e;
  @                  contains(e) <==> \old(contains(e)));
  @ ensures size == \old(size);
  @*/
public boolean add(int elem) {/*...*/}
```

Specifying remove()

```
/*@ public normal_behavior
  @ ensures !contains(elem);
  @ ensures (\forall int e;
  @                  e != elem;
  @                  contains(e) <==> \old(contains(e)));
  @ ensures \old(contains(elem))
  @         ==> size == \old(size) - 1;
  @ ensures !\old(contains(elem))
  @         ==> size == \old(size);
  @*/
public void remove(int elem) {/*...*/}
```

Specifying Data Constraints

So far:
JML used to specify method specifics.

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- consistency of redundant data representations (like indexing)
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How to specify constraints on class data, e.g.:

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- restrictions for efficiency (like sortedness)

data constraints are global:
all methods must preserve them

Consider LimitedSortedIntegerSet

```
public class LimitedSortedIntegerSet {
  public final int limit;
  private int arr[];
  private int size = 0;

  public LimitedSortedIntegerSet(int limit) {
    this.limit = limit;
    this.arr = new int[limit];
  }
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  public void remove(int elem) {/*...*/}

  public boolean contains(int elem) {/*...*/}

  // other methods
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```

Consequence of Sortedness for Implementations

`method contains`

- can employ binary search (logarithmic complexity)

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method `add`

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method `remove`

- (accordingly)

Specifying Sortedness with JML

recall class fields:

```
public final int limit;
private int arr[];
private int size = 0;
```

Sortedness as JML expression:

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(What's the value of this if `size < 2`?)

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(\forall int i; 0 < i && i < size;
                arr[i-1] <= arr[i])
```

(What's the value of this if `size < 2`?)

Where does the red expression belong in the spec?

Specifying Sorted `contains()`

can assume sortedness of pre-state

Specifying Sorted contains()

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```
/*@ public normal_behavior
  @ requires (\forall int i; 0 < i && i < size;
  @                              arr[i-1] <= arr[i]);
  @ ensures \result == (\exists int i;
  @                                0 <= i && i < size;
  @                                arr[i] == elem);
  @*/
public /*@ pure @*/ boolean contains(int elem) {/*...*/}
```

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public /*@ pure @*/ boolean contains(int elem) {/*...*/}
```

`contains()` is *pure*

⇒ sortedness of post-state trivially ensured

Specifying Sorted remove()

can assume sortedness of pre-state

must ensure sortedness of post-state

```
/*@ public normal_behavior
  @ requires (\forall int i; 0 < i && i < size;
  @                           arr[i-1] <= arr[i]);
  @ ensures !contains(elem);
  @ ensures (\forall int e;
  @                  e != elem;
  @                  contains(e) <==> \old(contains(e)));
  @ ensures \old(contains(elem))
  @         ==> size == \old(size) - 1;
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  @         ==> size == \old(size);
  @ ensures (\forall int i; 0 < i && i < size;
  @                          arr[i-1] <= arr[i]);
  @*/
public void remove(int elem) {/*...*/}
```

Specifying Sorted add() (spec-case1)

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  @ ensures size == \old(size) + 1;
  @ ensures (\forall int i; 0 < i && i < size;
  @                             arr[i-1] <= arr[i]);
  @
  @ also <spec-case2>
  @*/
public boolean add(int elem) {/*...*/}
```

Specifying Sorted add() (spec-case2)

```
/*@ public normal_behavior
  @
  @ <spec-case1> also
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  @ public normal_behavior
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  @ requires (size == limit) || contains(elem);
  @ ensures \result == false;
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JML Class Invariant

construct for specifying data constraints centrally

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We can do better, using

JML Class Invariant

construct for specifying data constraints centrally

1. delete blue and red parts from previous slides
2. add ‘sortedness’ as JML class invariant instead

JML Class Invariant

```
public class LimitedSortedIntegerSet {

  public final int limit;

  /*@ public invariant (\forall int i;
    @                           0 < i && i < size;
    @                           arr[i-1] <= arr[i]);
    @*/

  private /*@ spec_public @*/ int arr[];
  private /*@ spec_public @*/ int size = 0;

  // constructor and methods,
  // without sortedness in pre/post-conditions
}
```

JML Class Invariant

- JML class invariant can be placed anywhere in class
- (Contrast: method contract must be immediately before its method)
- Custom: place class invariant in front of fields it talks about

Instance vs. Static Invariants

instance invariants

can refer to instance fields of `this` object

(unqualified, like '`size`', or qualified with '`self`', like '`self.size`')

JML syntax: **`instance invariant`**

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can refer to
– static fields
– instance fields via explicit reference, like '`o.size`'

instance is default

if **`instance`** or **`static`** is omitted $\Rightarrow$ instance invariant!

Static JML Invariant Example

```
public class BankCard {

  /*@ public static invariant
    @  (\forall BankCard p1, p2;
    @     \created(p1) && \created(p2);
    @     p1!=p2 ==> p1.cardNumber!=p2.cardNumber)
    @*/

  private /*@ spec_public @*/ int cardNumber;

  // rest of class follows

}
```

Outline

Recall Specification of enterPIN()

```
private /*@ spec_public @*/ BankCard insertedCard = null;
private /*@ spec_public @*/ int wrongPINCounter = 0;
private /*@ spec_public @*/ boolean customerAuthenticated
                                    = false;

/*@ <spec-case1> also <spec-case2> also <spec-case3>
  @*/
public void enterPIN (int pin) { ...
```

Recall Specification of enterPIN()

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private /*@ spec_public @*/ BankCard insertedCard = null;
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public void enterPIN (int pin) { ...
```

last lecture:
all 3 *spec-cases* were **normal_behavior**

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keyword **`signals`** specifies *post-state*, depending on thrown exception

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`normal_behavior` specification case, with preconditions P,
forbids method to throw exceptions if pre-state satisfies P

`exceptional_behavior` specification case, with preconditions P,
requires method to throw exceptions if pre-state satisfies P

keyword **`signals`** specifies *post-state*, depending on thrown exception

keyword **`signals_only`** limits types of thrown exception

Specifying Exceptional Behavior of Methods

`normal_behavior` specification case, with preconditions P, forbids method to throw exceptions if pre-state satisfies P

`exceptional_behavior` specification case, with preconditions P, requires method to throw exceptions if pre-state satisfies P

keyword **`signals`** specifies *post-state*, depending on thrown exception

keyword **`signals_only`** limits types of thrown exception

Exceptions still have post-states in classes!

Completing Specification of enterPIN()

```
/*@ <spec-case1> also <spec-case2> also <spec-case3> also
  @
  @ public exceptional_behavior
  @ requires insertedCard==null;
  @ signals_only ATMException;
  @ signals (ATMException) !customerAuthenticated;
  @*/
public void enterPIN (int pin) { ...
```

Completing Specification of enterPIN()

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  @
  @ public exceptional_behavior
  @ requires insertedCard==null;
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public void enterPIN (int pin) { ...
```

in case `insertedCard==null` in pre-state

- an exception *must* be thrown (‘**exceptional_behavior**’)
- it can only be an `ATMException` (‘**signals_only**’)
- method must then ensure `!customerAuthenticated` in post-state (‘**signals**’)

signals_only Clause: General Case

An exceptional specification case can have one clause of the form

```
signals_only (E1,..., En);
```

where `E1,..., En` are exception types

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signals_only (E1,..., En);
```

where `E1,..., En` are exception types

Meaning:

if an exception is thrown, it is of type `E1` or ... or `En`

signals Clause: General Case

an exceptional specification case can have several clauses of the form

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signals (E) b;
```

where `E` is exception type, `b` is boolean expression

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signals (E) b;
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where `E` is exception type, `b` is boolean expression

Meaning:

> if an exception of type `E` is thrown, `b` holds in post-state

Allowing Non-Termination

By default, both:

- **`normal_behavior`**
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specification cases enforce termination

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diverges true;
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In each specification case, nontermination can be permitted via the clause

```
diverges true;
```

Meaning:

given the precondition of the specification case holds in pre-state,
the method may or may not terminate

Further Modifiers: non_null and nullable

JML extends the JAVA modifiers by further modifiers:

- class fields
- method parameters
- method return types

can be declared as

- **nullable**: may or may not be null
- **non_null**: must not be null

non_null: Examples

```
private /*@ spec_public non_null @*/ String name;
```

implicit invariant

`public invariant name != null;`

added to class

```
public void insertCard(/*@ non_null @*/ BankCard card) {..
```

implicit precondition

`requires card != null;`

added to each specification case of `insertCard`

```
public /*@ non_null @*/ String toString()
```

implicit postcondition

`ensures \result != null;`

added to each specification case of `toString`

non_null is default in JML!

⇒ same effect even without explicit 'non_null's

```
private /*@ spec_public @*/ String name;
```

implicit invariant

'`public invariant name != null;`'

added to class

```
public void insertCard(BankCard card) {..
```

implicit precondition

'`requires card != null;`'

added to each specification case of `insertCard`

```
public String toString()
```

implicit postcondition

'`ensures \result != null;`'

added to each specification case of `toString`

nullable: Examples

To prevent such pre/post-conditions and invariants: '**nullable**'

```
private /*@ spec_public nullable @*/ String name;
```

no implicit invariant added

```
public void insertCard(/*@ nullable @*/ BankCard card) {..
```

no implicit precondition added

```
public /*@ nullable @*/ String toString()
```

no implicit postcondition added to specification cases of `toString`

LinkedList: non_null or nullable?

```
public class LinkedList {
    private Object elem;
    private LinkedList next;
    ....
```

In JML this means:

LinkedList: non_null or nullable?

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public class LinkedList {
    private Object elem;
    private LinkedList next;
    ....
```

In JML this means:

- All elements in the list are **non_null**

LinkedList: non_null or nullable?

```
public class LinkedList {
    private Object elem;
    private LinkedList next;
    ....
```

In JML this means:

- All elements in the list are **non_null**
- Thus, the list is cyclic, or infinite!

LinkedList: non_null or nullable?

Repair:

```
public class LinkedList {
    private Object elem;
    private /*@ nullable @*/ LinkedList next;
    ....
```

⇒ Now, the list is allowed to end somewhere!

Careful with `non_null` and `nullable`

`non_null` as default in JML has been chosen recently.

⇒ Not yet well reflected in literature and tools.

JML and Inheritance

All JML contracts, i.e.

- specification cases
- class invariants

are inherited down from superclasses to subclasses.

A class has to fulfill all contracts of its superclasses.

in addition, the subclass may add further specification cases, *starting with* **also**:

```
/*@ also
  @
  @ <subclass-specific-spec-cases>
  @*/
public void method () { ...
```

Outline

Tools

Many tools support JML (see `www.eecs.ucf.edu/~leavens/JML/`).
Most basic tool set:

- `jml`, a syntax and type checker
- `jmlc`, JML/Java compiler. Compile runtime assertion checks into the code.
- `jmldoc`, like `javadoc` for Java + JML
- `jmlunit`, unit testing based on JML

This class does not require using the tools, but we recommend to use `jml` to check the syntax.

Outline

Literature for this Lecture

Essential reading:

in KeY Book A. Roth and Peter H. Schmitt: Formal Specification. Chapter 5 only sections 5.1,5.3, In: B. Beckert, R. Hähnle, and P. Schmitt, editors. *Verification of Object-Oriented Software: The KeY Approach*, vol 4334 of *LNCS*. Springer, 2006.

Further reading:

JML Reference Manual Gary T. Leavens, Erik Poll, Curtis Clifton, Yoonsik Cheon, Clyde Ruby, David Cok, Peter Müller, and Joseph Kiniry.
JML Reference Manual

JML Tutorial Gary T. Leavens, Yoonsik Cheon.
Design by Contract with JML

JML Overview Gary T. Leavens, Albert L. Baker, and Clyde Ruby.
JML: A Notation for Detailed Design

`http://www.eecs.ucf.edu/~leavens/JML/`